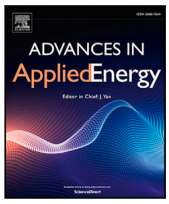
Advances in Applied Energy 18 (2025) 100222

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen



Electrifying aviation: Innovations and challenges in airport electrification for sustainable flight

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ARTICLE INFO

Keywords:
Airports
Electric aircraft
Charging strategies
Renewable energy
Electrification

ABSTRACT

The aviation sector is investigating opportunities to reduce pollution and to limit the dependence on fossil fuels. The design of new electric and hybrid aircraft requires airport developments to meet the need for charging. This review article provides an overview of recent developments and the latest research and innovation on electrification at and around airports. The paper describes technical innovations in electrified aviation, sustainable aviation fuels, and hydrogen, and the infrastructure needed at airports to meet the future electricity demand of electric aircraft charging. This study finds that plug-in charging of future electric aircraft will lead to elevated fluctuations in electric power demand at airports, while battery swapping has a more constant electricity demand. The review reveals a significant interest in energy storage and renewable energy systems to supply electricity and mitigate peak power at airports, suggesting high potential for batteries and solar power. Hydrogen for airport energy storage could support electric aircraft charging and be used as a fuel for hydrogen-powered aircraft. More research is needed regarding the optimal configuration of airport infrastructure to support electric aircraft development.

1. Introduction

The future energy transition in the transportation sector includes reducing emissions and pollution from all modes of transportation. Greenhouse gas emissions from the transportation sector increased in 2021 and 2022, after the reduced travelling and emissions during the COVID-19 pandemic [1]. Aviation is a major contributor to greenhouse gas emissions in the transportation sector [1]. To reduce emissions from the energy systems in the aviation sector, several measures are available, including new strategies for aviation routing [2], different types of aviation fuels [3], new aircraft designs [4], and new propulsion systems based on e.g., electrification [5]. The development towards more sustainable aviation relies on enhanced research and development, as well as new energy innovation.

Electric aircraft are one part of the solution receiving increased interest from industry and academia. The future electric passenger aircraft requires innovations and development of the energy systems, including, for example, development of light-weight electric motors and aircraft battery systems. The specific energy of batteries is a hindrance today, as the extra weight of batteries makes the aircraft too heavy to fly longer distances [6]. However, future battery development is expected to allow short-range passenger flights, and the development of future electric and hybrid-electric aircraft could play an important role in addressing the issue of emissions from the aviation sector. Moreover, the energy systems at the airport need to be developed to meet the future energy transition with different types of electric vehicles used at the airports. Following electric aircraft development, airport operations may face major changes in adapting to new service demands, such as electric aircraft charging. Different aircraft charging methods will affect the electricity demand differently. Several methods are available for airports to supply the electricity demand from aircraft charging, each with challenges and opportunities. The energy transition at airports also includes introducing electricity production from renewable energy sources and implementing energy storage systems. An overview of the energy transition in the aviation sector is shown in Fig. 1.

This literature review aims to provide an overview of the ongoing development of the future energy systems in the aviation sector, with a main focus on electrification in the aviation industry, with an investigation of new electric, hybrid-electric and turboelectric aircraft and charging infrastructure at airports. The need for an enhanced charging capacity relates to an increased number of electric vehicles (EVs) charged locally at airports, including the potential charging of future electric aircraft. This study analyses the different charging strategies that are useful at airports and the related requirements for the charging infrastructure. Furthermore, an overview and analysis of current electric systems at airports are presented, together with a discussion on how

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https://doi.org/10.1016/j.adapen.2025.100222
Received 4 March 2025; Received in revised form 16 April 2025; Accepted 2 May 2025
Available online 16 May 2025
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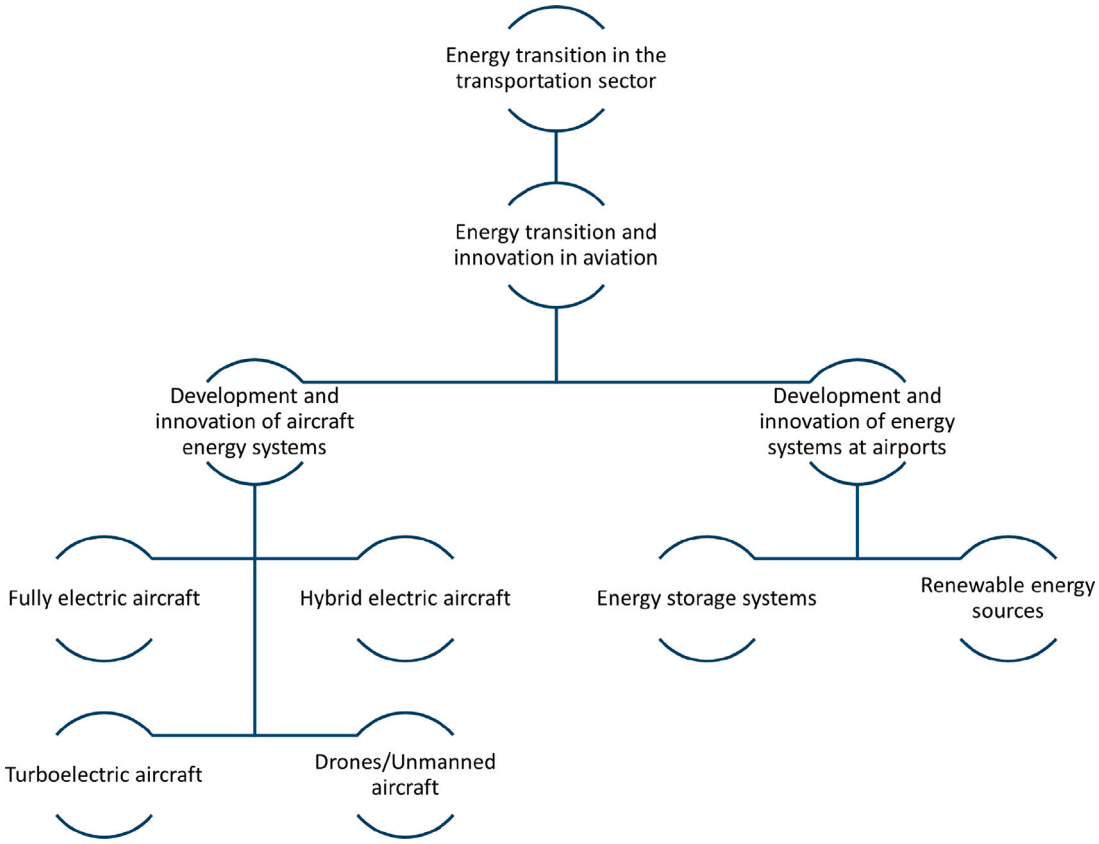

Fig. 1. An overview of energy transition and innovation in the aviation industry.

future aviation systems could affect the energy system at the airport. The study investigates the effects on the airport electrical system from renewable energy sources and energy storage systems at the airport, and the potential to deliver electricity for electric aircraft charging is discussed. To date, there is limited research providing an overview of both airport electrification and a presentation of ongoing development of electric aircraft, and this has been identified as a research gap. This study aims to contribute to the growing area of research on electrification in the transportation sector by summarising the recently published scientific literature on electrification for airports and sustainable energy systems in the future aviation sector. The importance and originality of this study is that it explores the challenges and opportunities for airport electrification with future electric and hybrid aircraft, based on recent scientific literature published in the field. The research provides a comprehensive overview of the ongoing airport electrification, to support the ongoing energy transition.

The paper is limited to studying the civil use of future aircraft. The main research question studied is: How will future electric aviation affect the electricity needed at airports, and what are the promising methods for providing enough electricity to charge future electric aircraft? The method used for this paper is an in-depth literature review based on scientific literature and reports, mainly from 2018 to 2025. The search phrases used included keywords as "airport", "electric aviation", "electric aircraft", "hybrid-electric aircraft", and "charging". Scientific literature was found in Scopus.com, IEEE Xplore and ScienceDirect.com.

The paper proceeds as follows: Section 2 categorises different types of electric aircraft. Section 3 describes different types of electric aircraft under development in the industry and different charging strategies to charge electric aircraft. Section 4 discusses the charging levels for electric aircraft and highlights the need for reliable access to high-power charging to limit the charging time. Section 5 describes the development of future airports. Section 6 discusses sustainable aviation fuels (SAF) and hydrogen for electric aircraft use. Section 7 discusses renewable electricity sources and their potential implementation in airports. Section 8 presents the potential of energy storage systems at the airport. Section 9 presents the results and discussion, followed by Section 10, which offers conclusions.

2. Classification of electric aircraft

Electric aircraft are characterised by receiving all or a share of the propulsive power from an electric motor. Electric aircraft are generally classified into three types depending on the configuration and share of propulsive power from the electric motor. The classification includes fully electric, hybrid-electric and turboelectric aircraft as proposed in [7].

2.1. Fully electric aircraft

The fully electric aircraft is characterised by using only electric energy transfer before the motor output to the propulsor, as seen in Fig. 2(a). Most fully electric aircraft developers design the aircraft with batteries as energy storage [8,9]. However, batteries store chemical energy converted to electrical energy within the closed battery system [10], and fully electric aircraft could use other energy storage techniques to convert stored energy to electrical energy within a closed system. Hence, the distinction between fully electric and other aircraft is based on the definition of propulsion components.

2.2. Hybrid-electric aircraft

Hybrid electric aircraft are defined as using two or more energy sources [7,11], where one energy source is a battery, as seen in Figs. 2(b) and 2(d). Hybrid electric aircraft can be divided into parallel hybrid and series hybrid [12–14], or a combination of both parallel and

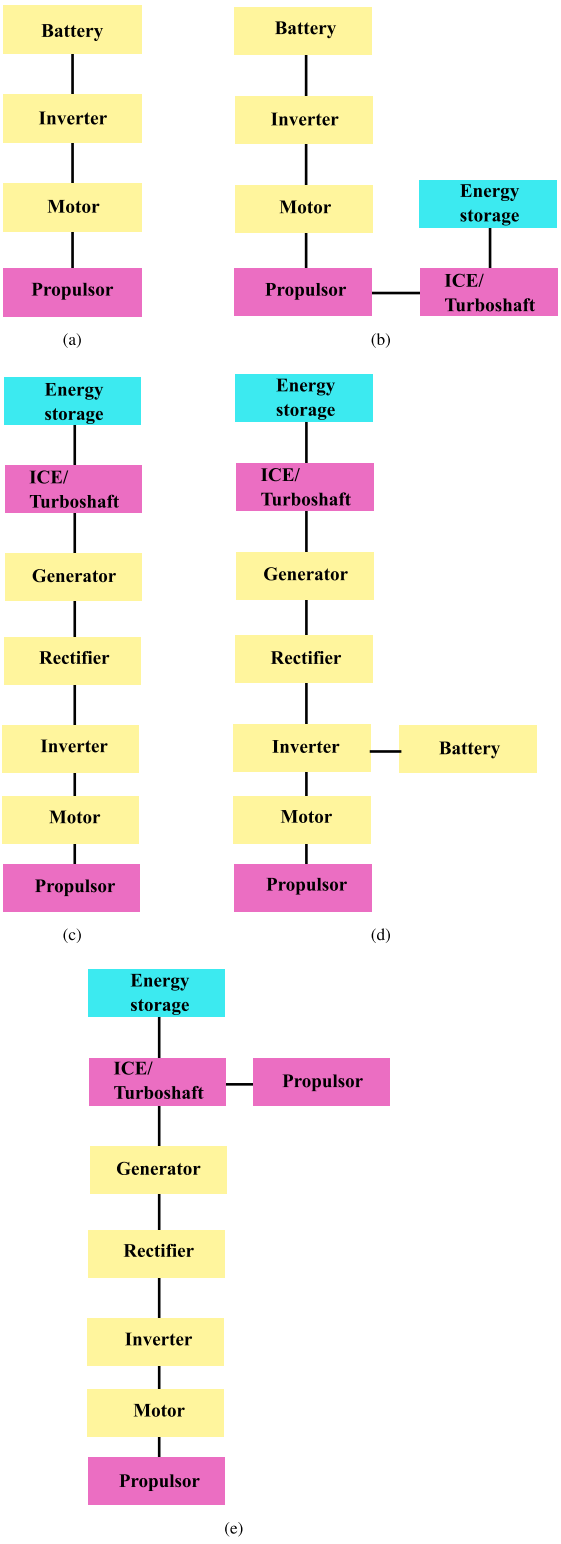

Fig. 2. Five possible electric aircraft configurations, based on [7], describing (a) fully electric-, (b) parallel hybrid-, (c) full turboelectric-, (d) series hybrid-, and (e) partial turboelectric systems.

series hybrid [15]. The parallel hybrid electric aircraft, shown in Fig. 2(b), use one electric motor and one internal combustion engine (ICE), or a turboshaft, to produce power to the same propulsor. Instead, series hybrid electric aircraft use an electric motor to supply a propulsor, as seen in Fig. 2(d), and a combination of batteries and ICE supply the electricity for the electric motor. The ICE, or turboshaft, can use several different fuels, such as SAF and hydrogen. A more comprehensive description of different configurations of hybrid electric aircraft is presented in [15].

2.3. Turboelectric aircraft

The third category of electric aircraft is the turboelectric aircraft. As presented in [7], turboelectric aircraft can be described as having an electric motor without using batteries to supply the electricity to the motor. Instead, the electricity is produced by an ICE and a generator [7,16–18].

Turboelectric aircraft can be classified into full turboelectric propulsion and partial turboelectric propulsion [19,20], as shown in Figs. 2(c) and 2(e), respectively. The full turboelectric propulsion system transfers all the power from the ICE to electric power and uses it in the electric motor [14]. The partial turboelectric system transfers parts of the power from the ICE to electrical power for the electric motor and parts mechanically to a separate propulsor [14].

3. Electric aircraft models and charging strategies of future electric aircraft

Several ongoing projects are developing electric aircraft within the aviation industry. However, most of the designed models are not yet available for commercial flights. Table 1 shows some of the ongoing design projects, together with parameters relevant to airport electrification.

Electric aircraft charging could take place during a flight or on the ground. Many electrified road vehicles can easily be charged by the road as part of the trip using public charging stations. In contrast, electric passenger aircraft would be complex to charge in the air during flight [21]. Therefore, charging electric aircraft on the ground at airports would be a more suitable and safe option, and this enhances the need for charging infrastructure at airports. Different possible charging methods that could be available at airports include plug-in charging, battery swapping, and mobile charging. The two most analysed charging methods are plug-in charging and battery swapping [22–25], however, systems with mobile charging stations are studied as well [26,27]. Fig. 3 illustrates the different charging techniques.

3.1. Plug-in charging with cable

Plug-in charging is today's most widely used charging method for electric vehicles, including electric aircraft [24]. Plug-in charging is based on a physical connection between the power grid, through a charger, to the batteries [28]. The existing electric aircraft charging systems, shown in Table 2, use power levels below 1 MW, and fast-charging techniques for large electric aircraft are not yet developed [29].

One challenge with plug-in charging is the required charging time [23]. Commercial aircraft typically have a turnaround time of 30–35 min, making it challenging to recharge a fully electric aircraft [23]. Previous research assumes a 45-min recharge time for hybrid electric aircraft [30], indicating that fully electric aircraft might need to extend today's turnaround time further. If the charging times for electric aircraft will be longer than the time needed to refuel an aircraft today, flight schedules at airports might need to be changed, enabling longer times with the electric aircraft on the ground and requiring longer times at a certain gate than the aircraft used today. Therefore, the charging times may have an impact on usage of the gate and the overall flight schedule at an airport, as well as any costs related to this [31].

Another issue related to the charging time is the power needed to charge the future electric aircraft. The charging power must be high to maintain short turnaround times, and charging multiple electric aircraft simultaneously could potentially risk the stability of the local power

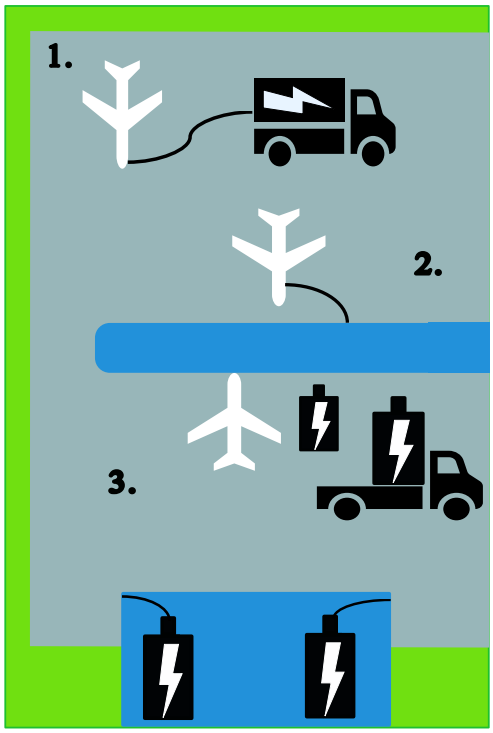

Fig. 3. Illustration of charging strategies at airports for electric aircraft. 1: mobile charging system. 2: plug-in charging. 3: battery swapping.

system. The short turnaround time and high charging power would result in highly fluctuating loads, from normal operations when no aircraft charge up to multiple times more during peak aircraft charging, especially for regional airports [31,32]. This could further stress the local grid and result in often unused capacity in the grid connections between the airport and the national grid, dimensioned to handle peak charging power.

There are also advantages with plug-in charging systems. The workload on the ground is comparably low for the charging process. One or two persons can connect the charger, preferably from a charging station on the apron or from a hole in the ground. The technology is also much more mature than other charging methods as it is commonly used in EVs today [24].

3.2. Battery swapping

Battery swapping means that the batteries in the aircraft are swapped to fully charged batteries at the airport, and the uncharged batteries are charged and used in other flights [33]. Few studies have been conducted on battery swapping for electric aircraft, and most of the literature refers to studies on other EVs [24,34].

The method is time-efficient to ensure a fully charged battery [33,35]. Removing used batteries and inserting fully charged batteries can take minutes, resulting in unchanged turnaround time [23]. Even if the total turnaround time remains mostly unchanged, concerns are raised regarding interference with other operations [23]. New procedures and new ground vehicles for battery transport will be needed. However, battery swapping is a promising technology for electric aircraft and is seen by airport operators as the charging method with the smallest effects on airport operation today [23].

Battery swapping also provides better functionality for grid services, as batteries are always stored and available to charge or discharge [35–38]. Grid services mean that the charging batteries can support the grid, receiving or providing power [35,39]. Batteries for grid services could be of interest for electric grids with electricity supply from renewable energy sources [39]. As battery swapping means several batteries are always connected to chargers, the stored batteries will act similarly to a stationary energy storage system. The literature on battery swapping stations for other EVs indicates that the number and capacity of the batteries impact the quality of grid-supporting service for renewable electricity production [40]. The charging strategy is important for grid support on the load side [40]. However, the potential of grid support depends on when most flights occur.

Some challenges with battery swapping still need to be solved. As batteries must be available at the battery charging facility, the number of batteries and chargers must be higher than the total need in the aircraft [24]. This leads to increased costs and a need for more storage area [23,28,37,38]. The battery swapping systems should also be the same for all aircraft and operators to enhance usability [28,37], which requires standardisation [38,59]. However, there are challenges identified with the standardisation of battery swapping [38]. For example, different types of aircraft would require different battery sizes and weights, which makes standardisation complicated.

3.3. Mobile charging

Another charging method is the mobile charging system [26,27]. A mobile charging system consists of a mobile platform carrying an energy storage system. The purpose is to enable remote aircraft charging, where an airport power system connection is not feasible. In [26], the mobile charging system is used to reduce the need for auxiliary power units.

A mobile charging system could also be an interesting solution for future electric aircraft charging [60]. As aircraft demand space at the apron, charging stations could preferably be placed at a certain distance. However, a separate charging station would require long cables, resulting in higher losses. By using a mobile charging system, the charger could get closer to the aircraft [60]. Another way to get the charger closer is by mounting it with the gate structure or putting it under the apron surface.

An early design for a mobile charging system for electric aircraft was proposed in [27]. The mobile charging system model consists of a 17.500 kg truck with batteries designed for 1.623 MWh of energy and charging at 2 MW for 30 min [27].

3.4. Other charging methods

Electric aircraft can also be charged outside the airport, e.g. while in flight. In-flight charging may include regenerative charging from braking, charging by aircraft-mounted energy production, or, for a series hybrid electric aircraft, battery charging using the generator and ICE. Regenerative charging is a charging method commonly used in non-plug-in hybrid cars [7]. Because a flight is planned and carried out with good navigational control, the aircraft can start to slow down and descend at an optimal position. Considering losses in power electronics and generative phases, turning off the power earlier and floating down is more efficient than flying an extra distance and then charging the batteries during a steeper descent and faster deceleration [21].

Solar power is a common option for electricity production mounted on the aircraft body [61–64]. This technology has potential for small and unmanned aircraft, yet the relative contribution by solar panels makes it unfeasible for larger aircraft [61–64]. However, the need for an extended range and the decreasing cost of solar cells could be incentives for future implementation [65].

Charging the batteries in flight using the combustion engine could be advantageous for hybrid electric aircraft, allowing the engine to run at optimal speed and recharging the battery as an extra load [66]. However, studies show that charging during flight results in negligible fuel savings and that the complexity of the control system and mechanical connections make this charging strategy impractical [66,67]. Another option would be to charge the battery using the combustion

Table 1
Different electric aircraft developers, showing the estimated entry time on the market, charging power, battery capacity, passenger capacity (PAX) and estimated range. The table also presents some ongoing R&D projects connected to airport electrification.

Ongoing R&D activities of electric aircraft.						
Estimated entry time	Name	Charging power [kW]	Battery capacity [kWh]	PAX	Range	Source
Today	Velis Electro - Pipistrel[a]	9	20	1	50 min	[41]
Before 2030	Heart Aerospace ES-30[a]	–	–	30	200 km	[42]
	ALIA CX300 CTOL[a]	–	267[c]	5	335 nm (620 km)	[43]
	Airbus Vahana[a]	–	38	–	50 km	[44]
	Airbus EcoPulse[a]	–	–	–	–	[45]
	Heart Aerospace ES-30[b]	–	–	30	400 km	[42]
	Heart Aerospace ES-30[b]	–	–	25	800 km	[42]
	Alice[a]	200–630	820–900	9	250 nm (~460 km)	[8,22,46]
	VoloCity[a]	–	–	2	20 km	[47]
	Volo- Region[a]	–	–	4	100 km	[48]
	Lilium[a]	–	–	–	–	[49]
	eFlyer[a] 2 & 4	–	–	2–4	–	[50]
2030–2040	Heart Aerospace[a]	–	–	30	300 km	[42]
	Heart Aerospace[b]	–	–	30	500 km	[42]
	Heart Aerospace[a]	–	–	30	400 km	[42]
	Heart Aerospace[b]	–	–	30	600 km	[42]
	Wright Spirit[a]	–	–	100	1 h	[51]
No date	X-57[a]	–	69.1 (47 useable)	–	–	[52]
Ongoing R&D activities in airports						
Airport or project name	Description of project					Source
Stuttgart Airport, Germany	Implemented battery for storage of energy from solar power to improve self-consumption and handle peak power.					[53]
TULIPS	The TULIPS project investigates different aspects of airport operations. Demonstration of unattended charging, modular charging stations to handle different voltage requirements, and a hydrogen handling and refilling demonstrator. Electrified airport operations and SAF handling will also be included in the project. The project includes airports in several countries, for example, Amsterdam Airport Schiphol in the Netherlands					[54]
Skellefteå Airport, Sweden	Multiple projects including drones, hydrogen aircraft, and electric aircraft charging. Demonstration of aircraft chargers and future tests of airport stationary battery for aircraft charging.					[55]
STARGATE	The STARGATE project includes multiple topics, including testing hydrogen operation vehicles. The project includes airports in several countries, for example Brussels Airport in Belgium.					[56]
GOLIAT	The project investigates technologies for large-scale liquid hydrogen refuelling. Ground operations for small-scale liquid hydrogen aircraft will also be demonstrated during the project. The project includes partners in several European countries.					[57]

[a] Fully electric.
[b] Hybrid electric.
[c] The energy is calculated based on the performance of BETA's charger [58].

engine while on the ground. However, this requires lower fuel prices for the combustion fuel than the cost of electricity at a charging station and would mostly be an option for remote charging, where no mobile charging system is available.

4. Charging levels

Only a few electric aircraft chargers are available today, as shown in Table 2. Standards for electric aircraft chargers are being developed for the conductive charging of light aircraft [68], and for megawatt charging [69]. There are small differences between the chargers designed for different types of vehicles. Therefore, chargers for electric aircraft will likely be similar to other types of chargers [60].

EV chargers can be classified in several ways [70–73]. One way to classify EV chargers relates to on-board and off-board location, as briefly described in Section 4.2. On-board chargers have converters on-board the aircraft and therefore transfer AC from the charger to the aircraft. The opposite technique is the off-board charger, having all power electronics outside the aircraft, transferring DC directly to the aircraft power system [28]. Chargers can also be classified into unidirectional or bidirectional power flow capabilities, depending on whether power can be transferred only to the battery from the grid or also from the battery to the grid, enabling vehicle-to-grid (V2G) functions [28]. A third way of classifying chargers is through the charging powers [70–73].

There are many standards for classifying EV chargers according to power, ranging from Level 1 to Level 3 or Level 4, depending on the standard [38,71]. The lower power levels use AC, and the higher levels use DC. Level 3 or 4 reaches around 250–400 kW, sometimes higher [38,71]. For charging powers up to and above 1 MW, the new Megawatt Charging System (MCS) standard is relevant, reaching up to 3.75 MW [75].

The amount of electricity that a power grid can supply to an airport, that is, the grid capacity, can be limited to some airports. This could be the case if the airport is located remotely and if the electricity grid is not built out entirely there. The capacity of the grid can affect the opportunity to charge an electric aircraft with high power at an airport. The enhanced electrification at airports can potentially support the grid with flexibility. Electric aircraft can be charged at different times, such as when the electricity price is low or when there is significant access to electricity produced from renewable energy sources to the grid, as well as be discharged at certain times, to add flexibility to the local grid.

Table 2
An overview of electric aircraft chargers available or discussed in the literature. Research charger means that the charger is suggested or used within research projects. Some of the charging systems can be chosen with different power levels.

Description	Power [kW]	Type
Charging systems for the Pipistrel aircraft [9]	3 10 15 20	Plug-in charger
Charging systems for the Electro Aero aircraft [74]	40 80 240	Plug-in charger
BETA charging systems [58]	40 320	Plug-in charger
Research charger [46]	200	Battery swapping
Research charger [22]	630	Plug-in charger

4.1. Kilowatt charging

All electric aircraft chargers available today have a power capacity below one megawatt, as seen in Table 2. A charger with kilowatt capacity could recharge swapped batteries, non-commercial aircraft without demands on turnaround time, hybrid-electric aircraft, and smaller fully-electric aircraft with few passengers [60]. One smaller electric aircraft is Velis Electro, used for pilot training, with a recharging time from zero to fully charged in 2 h at the designed charging power of 9 kW [9,41].

Batteries from aircraft using the battery swapping method could also be charged with kilowatt chargers because of the lower turnaround time requirements. The optimal configuration for the charging infrastructure for a short-range flight network using battery swapping was recently studied [46]. A sufficient flight network would require 900 kW of charging power at the hub airport and 4400 kW for the entire network, depending on the number of departures [46]. However, the electricity needs depend on how many aircraft and extra batteries are in the system [46].

Medium-sized fully-electric aircraft, such as Eviation Alice, with a passenger capacity of 9 passengers, would need higher power to recharge [8]. According to the literature, Alice is designed for 200–630 kW charging [22,46], resulting in a turnaround time between 80 and 270 min, far from the commercial turnaround times today. Multiple kilowatt chargers have also been suggested for charging larger, 50 passenger, hybrid electric aircraft, recharging in 45 min using four chargers on 350 kW each [76].

4.2. Megawatt charging

Megawatt chargers are important for charging larger electric aircraft, with a passenger capacity of more than 20 passengers, with short turnaround times using the plug-in method. These chargers are not available for aircraft today. However, they are being developed for electric truck transports [77,78], and electric ships [79].

The current target for electric car charges is 1 MW [80], but larger chargers are discussed, and the MCS standard under development will include charging up to 3.75 MW [75]. A capacity of 1.1 MW was concluded sufficient for a truck fleet in [81], while another study estimated the maximum useful charging limit for trucks to be 2.8 MW [75]. Heavier transports would need more power, and charging systems for ships have already reached 10.5 MW [79]. Medium-sized fully-electric aircraft could charge using the MCS standard, following the development of truck chargers. However, larger fully-electric aircraft with more than 20 passengers are anticipated to need more power than the MCS could provide, approaching the power transfer levels of ships.

Megawatt charging also has some disadvantages compared to lower charging powers. One disadvantage is the potential degradation of batteries when charged with high power, especially if the battery is already partially charged or if charging takes place at low temperatures [38]. High-power operations such as charging [82], take-off, and climb, generate more heat, an important factor for battery lifetime and performance, than other operation stages [38,83]. Especially charging is challenging because of longer high-power operation compared to e.g. take-off, combined with reduced cooling effect from lower wind speed [60,84].

Converters and other charging equipment are predicted to be placed outside the aircraft to reduce thermal stress and mass from charging converters and additional cooling systems inside the aircraft [85]. However, this results in potential problems for airport operators, as more high-power equipment must be stored around the terminals, and other operations must keep a safe distance from such equipment [23]. Some integrated on-board chargers using the existing drivetrain in the aircraft are suggested, resulting in lower costs and fewer challenges on the apron [86]. However, mass will be added from the additional cooling systems to reduce the increase in thermal stress, with weight already being an issue.

5. Development of airports for future electrified aircraft

Modern airports are divided into airside and landside [87]. Fig. 4 illustrates the division between airside and landside, and illustrates what a future full implementation of renewable energy and energy storage could look like. The fully electric and hybrid-electric aircraft will mainly be charged on the ground and at an airport, taking place on the airside of the airport, thus not affecting the landside. However, increasing usage of EVs on airside and landside and subsequent charging will affect both sides of the airport [88,89].

5.1. Airside

The airside of the airport includes runways, gates, aprons, and taxiways with support systems such as navigation lights, and will be affected by electric aircraft in several ways. At first, the aircraft will be charged on the airside, using one or several of the different charging methods discussed in Section 3. The charging requirements will depend on how long the aircraft will stay at the gate. Longtime parking, such as overnight, requires less electric power than charging during turnaround [24]. However, longtime parking will also raise the demand for parking locations [31].

The electricity usage on the airside will also be affected by battery cooling or heating systems at the airport [23]. Plug-in charging will require external temperature regulation at the gate as batteries have specific temperature ranges to operate safely that might be exceeded during warm summers or cold winters [38]. The number of gates with temperature regulation will depend on the number of electric aircraft connecting to the airport [90]. Temperature regulation will also be used in battery storage areas if a mobile charging or battery swapping method is used [23].

As the use of electric aircraft is limited by range, the energy surplus on board will be kept to a minimum. This means that movement between terminals and runways, mostly done by the aircraft itself today, could potentially be done by a tug [23]. However, tugs would increase the complexity of airside operations, and other solutions may be preferred. Power transfer units from the tug to support aircraft systems while waiting for take-off may also be needed, especially in the event of delays [23]. These power transfer units may be charged on the airside with other electrified service vehicles and contribute to airport electricity demand [89]. If tugs are used, they may, like other service vehicles, be electric. The total number of service vehicles will depend on the number of arriving and departing aircraft [91]. These vehicles will require frequent charging, with capacities up to 500 kW [91]. With both vehicles and power transfer units to charge, electrified airside operations will enhance the airport's electricity need. Renewable energy sources could also be located around runways and taxiways, as discussed in Section 7, contributing to airport electricity generation.

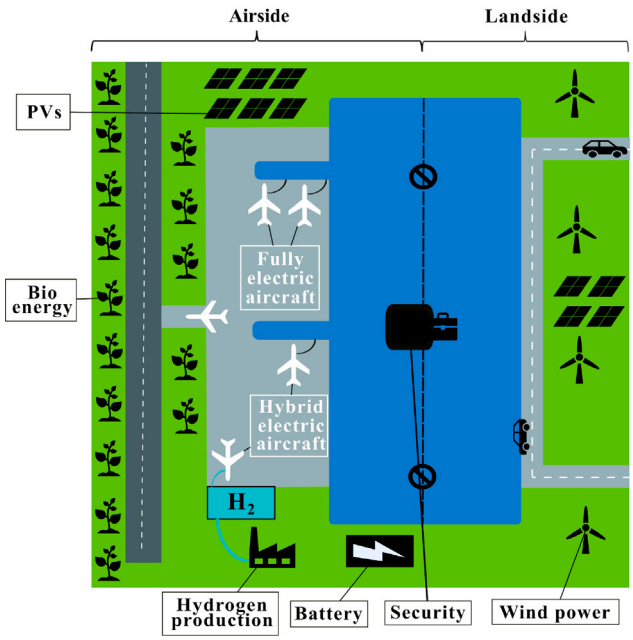

Fig. 4. Illustration of airside and landside of a future airport. Suggested implementation of renewable energy sources, including PVs, wind power, and bio energy, and energy storage such as batteries and hydrogen production facilities is also illustrated.

5.2. Landside

The airport's landside contains large parts of the terminal buildings with inside operations and car parking [87]. Electricity use on the landside will not be affected by electric aircraft charging. However, with ongoing electrification, the landside might be subject to increased EV charging, affecting the need for electricity and the airport grid. The landside of the airport could also be used to install more renewable energy sources to increase the electricity production. Solar power and biomass production could be placed on both airside and landside, while wind power is mainly limited to landside use.

6. Fuels for future electric aircraft

While battery electric aircraft reduce in-flight emissions to zero [92], they are limited in range by the current energy density of batteries [6,93,94]. To reach longer distances, other fuels are needed and can be used in non-electric, turboelectric, or hybrid electric aircraft [60]. Two fuels are discussed mainly for turboelectric and hybrid electric aircraft, SAF and hydrogen, both useful for different flight ranges [14,20,30,95–98]. Although refilling these fuels uses little to no electricity, the production of SAF and hydrogen could be located at the airport, increasing the electricity demand.

6.1. Hydrogen

Hydrogen as a fuel can be used in two ways for aircraft propulsion: through fuel cells or combustion [99]. Hydrogen combustion produces more power than fuel cells and is most suitable for medium to long-range flights, while fuel cells are more suitable for short flights [99]. Fuel cells produce electricity and are only possible in full turboelectric, series hybrid, and in a mixed configuration between series and parallel hybrid configurations. Usage in all configurations can reach zero emissions depending on the production method and the energy source [99–102].

Hydrogen can be stored in gaseous or liquid form or in a combination of both [103]. Gaseous hydrogen is seemingly not a viable option for aircraft, as the volumetric energy density is too low to fix a tank inside the aircraft body [101,104]. Liquid hydrogen is more promising but requires temperatures less than minus 253° C and should be stored in cryonic tanks [103]. These tanks could be fixed inside the aircraft structure, but the complexity of the tank leads to a high weight, and liquid hydrogen storage in aircraft is therefore a challenge with today's technology [93,103,104]. However, the use of liquid hydrogen as aircraft fuel would be promoted by development in tank structure. Liquid hydrogen would also demand an aircraft redesign for on-board storage, as wing storage, typical for modern aeroplane fuel storage today, is not a viable option due to the large surface area to insulate [101,105]. One design solution is to place the hydrogen tank inside the aircraft's main body, converting part of the passenger area to hydrogen storage, reducing the surface area to insulate [104]. Loss of passenger capacity could be compensated by increasing the aircraft length [106]. Studies have shown that a main-body tank of liquid hydrogen in cryonic or high-pressure tanks would be possible for hydrogen flights [106]. A mixed gaseous and liquid form increases the density but demands an advanced tank design to handle pressure and temperature, and is not common in hydrogen aircraft designs [103].

6.1.1. Hydrogen production

Several hydrogen production methods are available [107]. Sources such as water, fossil hydrocarbons, or biomass can be used, where fossil hydrocarbons must be combined with a carbon capture system to achieve decarbonisation of the aviation industry [108]. Electric energy is a major production component in electrolysis, electrophotolysis, bioelectrolysis, and thermoelectrolysis [109], of which electrolysis is the most common and least CO_2-emitting technology [110,111]. However, CO_2-emissions depend on the type of electricity source used, and zero emissions are achieved with renewable energy [105]. The energy source is also vital for the financial sustainability of hydrogen aircraft [99].

Electrolysis for hydrogen production uses electricity to split water into hydrogen and oxygen [112]. There are several methods of electrolysis. The methods with the most substantial production volume have an energy demand of >50 kWh/kg hydrogen [96,111–114], aiming for 48 kWh/kg in 2030 [114], and <42 kWh/kg in 2050 [96].

Hydrogen production for aircraft fuel must also include liquefaction to reach liquid hydrogen. The energy consumption for liquefaction is generally between 11.9 and 15 kWh/kg of liquid hydrogen [115–117]. It is prognosticated to reach below 9 kWh/kg of liquid hydrogen in a long-term perspective [115].

6.1.2. Hydrogen demand for flights

The introduction of hydrogen flights would require a lot of electricity for hydrogen production, assuming electrolysis is the production method. The energy demand to produce hydrogen for aircraft fuel was studied in [105]. In the study, 83% of global long-haul flights (range more than 4800 km) were assumed to use hydrogen combustion for aircraft propulsion. The electricity needed to produce the required liquid hydrogen was calculated, considering electrolysis, liquefaction, storage and filling of the aircraft tank. The flight network was concluded to require 2.91 TWh of electricity per day, assuming state-of-the-art technology in 2022 [105]. The hydrogen consumption for long-haul flights was estimated to 5.83 gH_2/passenger km [105].

An overview of the energy demand for single flights is presented in Table 3, showing hydrogen propulsion using gas turbines and fuel cells.

6.2. Sustainable aviation fuel

Another alternative fuel discussed in the literature is SAF, a fuel based on organic or non-organic compounds [118]. SAF have similar properties as normal aviation fuels today [119], making it a good option for long-haul flights [95]. However, flights using SAF emit

Table 3
Properties of proposed hydrogen flights with gas turbines (G.T.) and fuel cells (F.C.). Calculated energy values based on electrolysis of 50 kWh/kg and liquefaction on 11.9 kWh/kg hydrogen, based on estimations in [112] and [117].

	G.T. [101]	FC. [101]	F.C. [101]	G.T. [105]
Year	–	2021	2050	2022
Range [km]	4250	3580	4640	13,890
Used fuel [ton]	6.04	4.63	5.68	32.39[a]
E Liq.&Elec. [MWh]	373.9[a]	286.6[a]	351.6[a]	2005[a]
PAX	242	242	242	400
Total electricity [Wh/pas km]	351[a]	321[a]	313[a]	360[a]

[a] Calculated value.

CO_2 during combustion, compared to hydrogen and fully electric aircraft [92,93,120]. The sustainability of SAF flights is achieved through the circularity of the original feedstock. Feedstock can also be used to categorise SAF production into bio-jet fuels and CO_2 based fuels, both subject to numerous production alternatives [121,122].

6.2.1. Bio-jet fuel

Some early reviews of SAF production options comprehensively covered the production pathways and properties of bio-jet fuels [119,122,123]. Produced from biological material, bio-jet fuels are considered sustainable, and some parameters are advantageous compared to fossil-based jet fuel, such as higher energy density and lower climate impact in combustion [119]. Several different projects have tested bio-fuels in different jet engine setups in shares up to 100% [123]. Constructed production plants use mainly hydrotreating technology, adding hydrogen to the production process [119]. Although hydrotreating processes put a demand for hydrogen, the most pressing issue is access to biomass. A case study of the financial willingness to pay for bio-jet fuels in Sweden found that, using simplified assumptions, converting all the aircraft in Sweden to bio-jet fuels would demand between 9 and 15% of all available biomass in Sweden, competing with usage for road transport and district heating [124]. The potential biomass production on the airport is thus unlikely to result in enough feedstock for a bio-jet fuel production facility, and nationally adopted techniques for biofuels are needed based on the available biomass [119]. These issues make an on-site bio-jet fuel production facility less probable, and bio-jet fuels are likely to be produced in centralised production facilities covering a range of products and with a more diversified supply of biomass. Biojet fuels are therefore unlikely to affect the airport electricity demand.

6.2.2. CO_2 based production

Another way of producing SAF is by using CO_2 and hydrogen or water in a power-to-jet fuel plant [119,121]. An energy analysis of a power-to-liquid plant was performed in [121], including electrolysis for hydrogen production to produce SAF. Using a Fischer–Tropsch reactor, the process investigated is similar to that of bio-jet fuel discussed previously, but with a different carbon source. The electric power used was 271 MW, of which 200 MW was for the electrolyser, while the output SAF was 105 MW, with several other output hydrocarbons not included [121]. As for hydrogen, it is possible to place the electrolyser on airport grounds. However, the need for CO_2 of high purity and in large amounts, together with the variety of products, make this kind of production unit more suitable to place elsewhere, in connection with a CO_2-heavy facility. Hence, the CO_2 based production unit is not reasonable to place near an airport and would not affect the airport's electricity needs.

7. Electricity production at airports

The main source of electricity at most airports is the national electricity grid. Electricity is delivered to the airport through one or several grid connections, where the airport grid connects to the national grid. The capacity of the grid connections depends on the estimated airport electricity demand. Electric aircraft charging will increase airport electricity demand and may require new grid connections with higher capacity [32].

In addition to electricity consumers, airports can become electricity producers, using renewable energy sources deployed within the airport area [125]. Several renewable energy sources could be used, such as solar power [126,127], wind power [128,129], or biomass [130].

7.1. Solar power at airports

Solar power using photovoltaics (PV) in airports has received increasing interest in recent years [126,127,130–134]. Case studies implementing solar power have been conducted in a few airports around the world, investigating the potential electricity production and, in some cases, self-sufficiency.

Several studies have investigated a 12 MW PV installation at Cochin Airport, India [135,136]. The PV facility produced 48 MWh on average each day, with an average utilisation factor of 20%. Demonstrating the potential of PV to produce the necessary power within an airport, it was concluded that solar power production in India coincides with power demand due to cooling needs [135]. A similar correlation between PV production and airport demand has been concluded for tropical regions [137]. Simulations of PV installations in China show that production ranges from 174 kW to 122 MW depending on the airport [132], and Egyptian airports have an estimated solar power output of 3 GW if fully explored [138].

At Incheon International Airport in South Korea, 15.7 MW of solar power are in operation [139], while a potential of 60 MW is identified [140]. A 2 MW roof-mounted PV system is used at the local airport in the Galapagos Islands [141], while the Kamuzu International Airport in Malawi uses an 830 kW PV plant [142]. Moshoeshoe I International Airport in Lesotho has a 281 kW PV plant installed [143]. In the US, Denver International Airport has installed a 10 MW solar farm on the airport grounds [144]. For more US airports with PV systems installed, see [145,146]. In 2021, construction of a 14 MW solar power park at Rotterdam the Hague airport began [147]. In Germany, Nürnberg airport has started installing a 13.4 MW solar park [148], and Neuhardenberg has a 145 MW solar park installed around the runway [149].

For the northern hemisphere, the effects of PV and a battery energy storage system with more electric aviation and electric vehicles have been analysed for a Swedish airport [127]. Although PV systems produce substantial amounts of electricity, the negative correlation between power demand and PV production in the northern hemisphere results in a low effect of PVs on peak power demand from the grid [127]. Hence, the necessity of a battery to reduce peak power demand is thoroughly demonstrated. The investigated PV panels result in a peak production below 1.2 MW and a yearly electricity production below 1.1 GWh, depending on the studied PV location [127]. For more studies on installed PVs in airports, see [133,142].

Solar power also brings some challenges for airport operations, as stated in several research articles [150–152], all highlighting potential risks. The most extensive definition defines seven risks connected to airport-installed PVs; glare occurrence, interference with communication and surveillance systems, PV penetration into airspace, accidental intrusion into PV system, detachment of PV system, strike by birds, and electric hazards [152].

Glare or glint from solar panel reflections may cause temporary vision loss for pilots and airport staff [133,153]. Four main actions are suggested to reduce the risk of glare; choose PVs with an anti-reflective coating, roughen the surface glass, reorient the PV modules, and prepare an emergency plan [153]. Although the severity of the risks of glare is debated, ranging from high [152] to low [151], problems caused by glare from installed PVs at the Manchester-Boston airport

led to parts of the PV system being temporarily covered while redirected [154]. Of the suggested actions to reduce glare, adjusting the tilt and orientation angle are the most promising solutions [155], and the risks of glare can potentially be avoided completely by thorough planning before installation [153,156].

PVs can also interfere with communication and surveillance systems, including radar, by electromagnetic interference and radar signals reflecting in metal structures in PVs [151,152,157]. For ground-mounted PVs, high underground current transmission reduces electromagnetic waves [151]. However, roof-mounted PVs send stronger electromagnetic waves that could pose a problem for communications and surveillance and should be mounted cautiously. To mitigate risks, electromagnetically shielded frames and cables could be used, and a safety distance from communication systems should be ensured [157]. A safety distance could also reduce the risk of heat gathered during the daytime interfering with infrared systems, especially during dusk [151].

Another risk is PV penetration into airspace, including mounting too near the runway or in the line of sight for airport control operators [152]. The low height reduces the risk, but sufficient security distance should be taken to runways [151,152].

Accidental aircraft intrusion into PV systems during veer-off accidents was concluded as a major risk in an interview study [150]. Runway excursions, including veer-off, in which the aircraft travels outside the runway during take-off or landing, are among the most common aircraft accidents [158,159]. A veer-off accident into PV systems along the runway could start a fire on the ground or in the aircraft, and the reduced mobility of the rescue teams could increase the rescue time [150,152]. Evacuation is also aggravated, including a severe risk for casualties with passengers and crew moving near high-power equipment [150]. Sufficient safety distance between aircraft movement areas and PV systems could reduce these risks [152].

PV systems near runways could also lead to objects detaching and entering the runway or striking aircraft arriving or departing [150,152,157]. The risk is especially high during extreme weather events and maintenance [157]. Visual checks around the runway after maintenance and weather events should be ensured [150], and fences could be used around PV systems to prevent objects from entering the runway [157].

Another potential risk brought up in the literature is collision with birds, as birds seek cooling shadows and search for insects that live in areas with PVs installed [152]. An early study of bird usage of PV systems counted the number of birds in different airport grasslands and PV systems, and found that PV systems attracted a higher number of small birds [160]. However, the study also found that larger birds, causing more severe collisions with aircraft, were less frequent in airport areas with PV systems installed. Installing PV systems on airport grasslands could therefore reduce the risk for severe bird collisions, though acknowledging large uncertainties [160].

As described by [152], electrical hazards are another risk of airport PVs. Although the severity and probability of electrical hazards are high [150], the right precautions, such as securely connecting cables and covering PVs during maintenance, would reduce risk to acceptable levels [150].

7.2. Wind power at airports

Wind power is an interesting option for local electricity production in or near airports [31,125,128,129], and can also be used outside of the airports to provide electricity produced from renewable energy sources to the electric grid. For wind power in airports, there could be challenges due to the tower height and radar interference [130,161]. Radar interference could be solved by mounting radar sensors on the turbines to send measurements to the main radar station, providing a complete radar image [130]. However, the tower height limits the potential, and full-scale wind power is preferably located outside the airport area [162–165]. Although potentially problematic, wind power is installed at some airports today [145]. Boston Logan International Airport has several 10 ft high 1 kW building-mounted wind turbines, and Burlington Airport has a 100 kW utility-scale wind turbine at the airport [145]. At Las Palma Airport, two 660 kW wind turbines are located outside the terminal building, and East Midland Airport has two 250 kW wind turbines [166].

7.3. Other power sources at airports

Other sources of electricity could be placed at the airport, such as geothermal power and biomass production and combustion [125]. Geothermal power is used at Incheon International Airport [140], with an installed capacity of 8 MW [139]. Portland International Jetport also has geothermal power [145], as well as Montreal Pierre Elliott Trudeau International Airport [166]. Although used, geothermal power depends on the specific geology of the airport location, and not all airports can use it [125].

Biomass production from the airport could be used in a combustion engine to generate electricity or for bio-jet fuel production. However, an overview of the possibility of biomass production in US airports found that biomass production at airports is not enough for a biofuel production facility [130]. Instead, it could contribute to a regional production strategy [130]. Imported biofuels could still generate electricity at the airport, as used at Munich Airport in a combined power and heat plant [167].

8. Energy storage at airports

Energy storage is an interesting solution for airport use. It can support the airport grid during high demand or store electricity from intermittent renewable energy sources [10,132]. Many energy storage systems are available [10]. The most frequently discussed for use in airports are batteries [24,127,140], hydrogen [22], or a combination of both [30,168].

8.1. Batteries

Compared to hydrogen, batteries have a fast response time and high charge and discharge efficiency of around 95% each [169]. Batteries as energy storage in airport electrification studies are often combined with solar power [24,30,127,140,168]. Energy capacities between 1 and 2.5 MWh have been investigated for self-consumption improvements with solar power installed [127]. Some studies have also included hydrogen in the system [30,168]. All studies have identified an increased self-consumption with batteries [30,127,168]. In a simulation study of an airport with future electric aircraft charging, a 2.2 MWh battery, connected to support airport load and aircraft charging, was combined with solar power hypothetically located at the airport [127]. The battery was found to increase the self-consumption of electricity produced by a PV system at the airport from 80% to between 80.4 and 98.3% depending on the battery management strategy, although it could not cover the load of electric aircraft charging. The system also had a high ability to reduce peak power in configurations without PVs [127]. Larger energy capacities have also been studied, and 142 MWh of storage capacity combined with PVs was found sufficient to supply a 40% load increase compared to normal operations at Incheon International Airport, without including any electric aircraft [140].

Batteries have already been implemented at some airports. Copenhagen Airport has implemented a 1.2 MWh battery to support the electrification of the airport and surrounding services [170], and Schiphol Airport is testing a battery to supply electricity to ground power units for remotely parked aircraft [171].

Table 4
The main opportunities and challenges for different charging methods and for the production of fuels for electric and hybrid electric aircraft are described. Colours based on potential for future usage, green: high potential, yellow: moderate potential, red: low potential.

Charging methods		
Technology	Opportunities	Challenges
Plug-in charging	Mature technology. Lower resource demand compared to other charging methods.	High and fluctuating power demand. Long charging time or high power. High effects on airport systems. Fast battery degradation.
Battery swap charging	Time efficient. Stable power demand. Potential grid services. Less battery degradation than plug-in.	Resource demanding. Medium effects on airport operations. High requirements on standardisation.
Mobile charging system	Low effects on airport operations. Allow remote charging.	Long charging time or high power from the mobile charging system. Fast battery degradation.
Hydrogen	Production can balance airport load. Dual purpose.	Comparably low efficiency. Access to feedstock depends on location.
SAF	Compatible with existing aircraft and airport systems.	Comparably low efficiency. Feedstock limitations on airport. Off-airport location is beneficial.

8.2. Hydrogen storage

Hydrogen storage is commonly discussed in connection with airports in the literature, either as fuel storage for hydrogen hybrid electric aircraft [30] or remote power units [168], or as energy storage for later conversion into electricity to support the airport grid [22]. It enables higher storage capacities than batteries [169], and surplus hydrogen can be used to refill hydrogen aircraft. However, storage of electrical energy through hydrogen requires conversion from electricity to hydrogen and back, subject to comparably low efficiencies, around 40%–70% and 40%–60%, respectively [112,172].

A recent study of electric aircraft and hydrogen investigated plug-in charging and battery swapping for electric aircraft [22]. The study included solar power and hydrogen storage with an external hydrogen supply. Scenarios of varying V2G contributions from parked EVs while operating the airport as a microgrid were investigated. The study showed that higher fuel cell conversion rates, from 1 MW to 8 MW, increased the airport's function as a microgrid. However, increased conversion capacities came with a high investment cost and were only feasible when microgrid operations were threatened. The study also showed that V2G reduced system costs and improved airport operations [22].

9. Discussion and results

The results of this review are summarised in Tables 4, 5, and 6. Table 4 specifies the potential electric aircraft charging methods and fuel production methods along with the opportunities and challenges identified with each method. Table 5 shows potential electricity production methods to support electric aircraft charging at airports. Table 6 displays potential energy storage methods for airport use. The technologies are coloured according to the potential for future usage at the airport (green: high potential, yellow: moderate potential, red: low potential).

Charging strategies will change along with electric aircraft development. Early electric aircraft charging is expected to use the plug-in charging method, as it is a mature technology with low implementation cost and complexity compared to other charging systems. Due to the comparably short range, below 500 km for fully electric aircraft and below 1000 km for hybrid electric aircraft, and low passenger capacity of early electric aircraft described in Table 1, less energy will be needed in the aircraft batteries, and turnaround times could be maintained with lower charging power. Depending on the charging power and the number of aircraft, new grid connections might be necessary to cover the simultaneous charging of multiple aircraft. When cost-effective, mobile charging systems could be used instead of, or as an alternative to, plug-in charging to allow remote charging. These charging methods will result in a fluctuating power demand for the airport, alternating from no demand to an electricity demand of several megawatts, depending on the number of aircraft. As larger electric aircraft are developed, necessitating faster charging, battery swapping could become a solution to reduce charging power and battery degradation. The implementation of battery swapping will depend on the introduction of standards, allowing the same battery to be used in several different aircraft. However, standardising the battery system over different aircraft could become challenging with different requirements for energy and range for different aircraft, leading to different battery weights. Another hindrance of battery swapping could be the cost and complexity of setting up the system while still operating earlier developed plug-in charging aircraft in parallel. This could potentially block the introduction of battery swapping, motivating developers to focus on plug-in charging techniques instead. If battery swapping is implemented, other charging methods will remain available for existing and new aircraft with shorter ranges. Therefore, airport power demand will continue to fluctuate while adding a near-constant charging demand for the battery swapping station.

From a cost and complexity perspective, plug-in charging is a promising option. Battery swapping demands high investment costs initially, including extra, swappable batteries and swapping systems along with storage facilities. The operational cost for battery swapping is lower, with reduced battery degradation and a more evenly distributed power demand curve, reducing the cost for power capacity. However, without standardisation, the complexity could be too high. Plug-in charging of future electric aircraft at airports also has a notable initial cost, including installing chargers and potentially new cables with higher capacity. Nonetheless, the initial cost will likely be lower than for battery swapping. Mobile charging could be an option to plug-in charging to reduce the cost of installing chargers at the gates. On the other hand, mobile charging requires trucks and extra batteries, resulting in extra initial costs comparable to or exceeding the initial cost of plug-in charging systems. Mobile chargers will also increase the complexity in airport operations, acting like a refuelling truck. This complexity is removed with plug-in charging in designated spots or at the gate. Plug-in charging is thereby beneficial from cost and complexity perspectives, at least in initial stages with comparably low charging powers and energies. With the development of higher charging powers, the operational cost of plug-in charging could become an issue at future electrified airports. Moreover, there is a significant cost related to the development of future aircraft types. There are still uncertainties about who should pay for the transition towards more sustainable aviation. Therefore, it is recommended that future research focus more on the economic perspective of electrification in the aviation industry.

Other fuel production may affect airport electricity demand in the future. The lack of feedstock makes it unlikely for SAF to be produced

Table 5
Technologies for supplying necessary electricity to the airport and their main opportunities and challenges. Colours based on potential for future usage, green: high potential, yellow: moderate potential, red: low potential.

Electricity production		
Technology	Opportunities	Challenges
Solar power	The most airport compatible renewable energy source.	Several safety hazards to handle. Usability all the year depends on airport location. Intermittent.
Wind power	A good complement to solar power.	Regulatory challenges. Potential safety hazard. Intermittent.
Geothermal power	Predictable production. Low safety risk.	Implementation depends on the geology of the airport location.
Biomass	Low safety risk. No or low airport modifications are needed.	Biomass to biofuel conversion is inefficient at the airport.
Grid	Available infrastructure can be reused when low charging demand. Mature technology.	Infrastructure for high-power charging will be mostly over-dimensioned to cover peak power. High investment cost and high cost for power agreements.

Table 6
Energy storage systems for use at airports and their possibilities and challenges. Colours based on potential for future usage, green: high potential, yellow: moderate potential, red: low potential.

Energy storage		
Technology	Opportunities	Challenges
Battery	Decreases peak charging power efficiently. Potential support to normal airport demand.	High investment cost. Battery degradation depends on usage.
Hydrogen	Useable both for charging and filling up hydrogen aircraft. Long-term storability. Potential support to normal airport demand. Production flexibility allows surplus power use.	Low efficiency.

at the airport. Instead, hydrogen could be produced at the airport using surplus power from renewable energy systems or overcapacity in grid connections dimensioned for peak charging power. However, hydrogen production for use as electric aircraft fuel fully depends on hydrogen aircraft development, and hydrogen production for use as aircraft fuel therefore lies in the future.

Airports have a high potential for electricity production from renewable energy sources in the airport. Solar power is the most promising because of the vast open fields surrounding the runway and aprons. Although installation requires detailed planning, solar power could support excessive electric aircraft charging during peak production. However, intermittency is challenging, and charging only from solar power is not feasible without substantial energy storage capacities. Wind power could complement solar power in supporting electric aircraft charging, but challenges with tower height make it less suitable for widespread use. Wind power is also intermittent and may not reduce the need for energy storage or other sources of electricity. Geothermal power depends on geology and should be investigated when possible. However, it is not a method for every airport. Biomass is another renewable energy source that could be produced at the airport. Although biomass production comes with few risks and shows potential for airport location, the production of biofuels is unlikely to take place at airports. Therefore, biomass production at the airport will not result in direct airport electricity production.

Energy storage at the airport is an interesting alternative to supply electric aircraft charging. It can support electric aircraft charging and reduce peak charging power, thus reducing peak demand from the grid. This limits stress on the surrounding power grid and may reduce the cost of more extensive grid connections to the airport. Energy storage can also store electricity from renewable energy sources at the airport to increase self-consumption and, in some cases, allow for electric aircraft charging using only renewable energy. Batteries have a higher potential than hydrogen storage because of their high efficiency and mature technology. However, with the introduction of hydrogen-powered hybrid or turboelectric aircraft, the dual function of hydrogen can be an incentive for airport implementation. Airports aiming at complete self-support from renewable energy, without any electricity demand from the grid, benefit from the large potential storage capacity for hydrogen.

Table 7 suggests the type of electricity supply and energy storage to implement at the airport to support electric aircraft charging for different stages of electric aircraft development. The effects of each implementation are also presented.

The early stages of electric aircraft development with plug-in charging will add fluctuations to the airport's electricity demand. The amplitude of the fluctuations will depend on the charging power and the number of departures. Dimensioning grid connections to the airport based on peak charging demand will result in frequent overcapacity. While renewable energy sources could cover the need, the intermittency limits reliability, and thus renewable energy is unlikely to supply the charging electricity alone. Energy storage is an option that could store electricity during low demand and supply necessary power during peak demand, reducing the fluctuations to some extent and, in turn, reducing grid-connection costs. Further cost savings could be achieved by combining a battery with renewable energy systems and charging the battery with renewable electricity.

The eventual introduction of battery swapping will add nearly constant electricity demand to the fluctuating plug-in charging demand. As the load of the battery swapping station will be less fluctuating, dimensioning grid connections will not result in major overcapacity, making grid supply a viable method of covering this load.

With the introduction of hydrogen aircraft, hydrogen production could become an option and further smooth out fluctuating plug-in loads. The low efficiency makes hydrogen an infeasible option without dual usability as aircraft fuel. Hydrogen production can be regulated shortly and turned on when the charging load allows free grid capacity or renewable energy surplus. With hydrogen production at the airport, the airport's electricity demand from the grid could potentially become constant, using batteries and hydrogen to smooth the production fluctuations from renewable energy sources installed at the airport and the demand fluctuations from airport operations and aircraft charging.

The increased use of electric aircraft will change the way airports consume electricity. Research into the development of electric aircraft,

Table 7
Electrification strategy for airports following different stages of electric aircraft development. The effects on electricity availability at the airport are also described. Priority in falling order.

Stage	Technology	Effects
Plug-in, ≤2 MW	Battery Solar power	Smoothened power demand. Intermittent power production.
Battery swap + plug-in, ≥2 MW	Grid connection Larger battery More solar power	Increased power availability. Smoothened power demand. Intermittent power production.
Battery swap + plug-in + hydrogen	Hydrogen production More solar power, if possible Investigate wind power	Refill aircraft and supply electricity. Intermittent power production. Intermittent power production.

including charging methods, is important to understand the future demand for airport operations. Different renewable energy sources in different combinations could be used to supply the increased electricity demand. Future research should investigate combinations of electric aircraft charging methods to simulate stages of implementation. Electric aircraft charging methods should also be studied together with different combinations of renewable energy sources and energy storage systems to provide a broad understanding of possible solutions. Future studies of airport adaptation to electric aviation should also consider other EVs and the effects of more EV charging, but also the potential effects of V2G. To develop a full picture of future airport electrification, including evaluating the challenges and opportunities with new types of aircraft, additional studies will be needed, in particular studies that demonstrate real-world applications. In future investigations, it is recommended to introduce several pilot projects on electrification in airports and on electric or hybrid aircraft. Pilot projects can provide a better understanding of the impact of electrification in airport environments.

10. Conclusions

This literature review investigates the potential effects of future electric aircraft charging on airport electricity use and the options to mitigate these effects by implementing renewable energy sources and energy storage. Several projects on electrified aviation are ongoing, but only a few manufacturers have an electric aircraft on the market today. Three main electric aircraft charging methods are identified, each with its own characteristics. Plug-in charging is the most mature technology, yet it could be the most challenging for the airport grid due to high fluctuations in electricity demand. Mobile charging offers remote charging, reducing the need for terminal reconstruction. Battery swapping includes several technical and operational challenges for airports. However, battery swapping could also support the airport's electrical system because of the opportunity to charge the batteries over a longer time. A combination of renewable energy sources and energy storage is identified as the most promising method to supply electricity for electric aircraft charging. Opportunities and challenges with each renewable energy source in airports are identified, and a combination of different renewable energy sources together with energy storage could provide advantages for the future airports. Batteries are the energy storage technique with the highest potential for early airport implementation due to their high efficiency. The dual usability of hydrogen, following the introduction of hydrogen aircraft, makes it a viable option for future airport implementation.

CRediT authorship contribution statement

Martin Lindberg: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Jennifer Leijon:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was mainly funded by The Swedish Transport Administration (Trafikverket), as part of the research project: "Flygplatsens möjligheter och utmaningar i utveckling för elflyg, elektrifiering och hållbarhet (YourFlight)". The research was also financed by the projects "Ongoing electrification in the aviation sector: Interregional Perspectives on Infrastructure Investment Optimization for Flight Electrification and Decarbonization (ONGO:iFED)" funded by the Resilient Energy Systems Competence Center, and "Strengthened competence, risk management and technical-economic conditions for the transition towards battery-electric flights and sustainable electrification at national airports (TAKEOFF)", project number: P2023-01526, funded by the Swedish Energy Agency. This research was conducted within the STandUP for Energy framework.

Data availability

No data was used for the research described in the article.

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